Highly-integrated energy harvesting device for rotational applications utilizing quasi-static piezoelectric and electromagnetic generators

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ABSTRACT

This work addresses the design of an integrated energy harvesting system under production viewpoints. The system is developed to harvest energy from rotational movements. Therefore, a piezoelectric bending element – mounted on the rotational part - is actuated by magnetic force introduced by hard magnets installed in the fixed frame. This work concentrates on a high integration, the energy harvesting circuit, including rectifier, power management and storage is integrated in the structure of the bending harvester. Further the soft magnetic tip mass is equipped with a coil for electro-magnetic energy harvesting; the necessary electronic is also integrated in the structure. The paper addresses the special systems demands for large scale production. The production technology for a small series of prototypes is explained in detail. Performance tests of the device conclude this study.

Keywords: Energy Harvesting, Combining piezoelectric and electromagnetic conversion

1. INTRODUCTION

Technical progress is producing smaller and thus more mobile devices. One limiting factor is still the energy need of these devices in form of electricity. Today's batteries provide a high efficiency and high energy density, but they can only power a system for a limited time. Consequently, frequent maintenance or continuously battery recharging is required. Additionally, the desire for environmental friendly solutions exists. Energy harvesting technology is a possibility to come closer to autonomous systems. Possible sources include mechanical vibrations, temperature gradients and heat flow, light, rotation, radio waves, and even sound. Unfortunately, the performance of today's small size generators is very limited due to their energy density [1]. Harvester with a power level in the range of nano- up to milliwatts are already used to provide energy for e.g. autonomous wireless transmitter for system monitoring, to operate building automation and medical devices.

The most powerful sources for energy harvesting in industrial environments include vibration. These are often used by means of piezoelectric or electromagnetic transducer. Such generators provide the most power, when operated in their resonance frequency, since the deformation and thus energy is generated on the highest level for any given input. For uses with known environment conditions, this represents a good opportunity. For mobile applications with changing operating frequencies or transient sources of energy resonant operating systems are limited suitable, due to their small bandwidth. Active resonant adaptation and multimodal systems are a possibility to increase the power yield [2]. In this contribution a quasistatic approach is chosen to overcome the bandwidth limitation. The application scenario is a wireless sensor on a rotating machine part. The development and design of the quasistatic, holistic, integrated energy harvesting system. A new feature is the structural combination of a piezoelectric and an electromagnetic transducer. A piezoelectric bimorph and a coil are used as generator. The power converter and the power management electronics are integrated in one device. The harvested energy is caught as long as the energy is sufficient to operate the desired application. For excitation, magnets are placed on the fixed frame. The attractive force bends the generator element while passing. The deflection amplitude is approximately constant for a large frequency range, due to the consistently strong magnetic field. Consequently the deflection is well designable. The gradient of magnetic flux, and thus the induced voltage is significantly higher than in conventional vibration excited converters, because the coil leaves the magnetic field completely. If multiple magnets are arranged on the fly wheel, multiple actuations of the generator can be archived per revolution. This mechanism is also called frequency pumping.
Lallert et al. propose a system combining piezoelectric and magnetic elements. The construction based on the deflection of the piezoelectric elements caused by an attracting or repulsive magnetic force [3].

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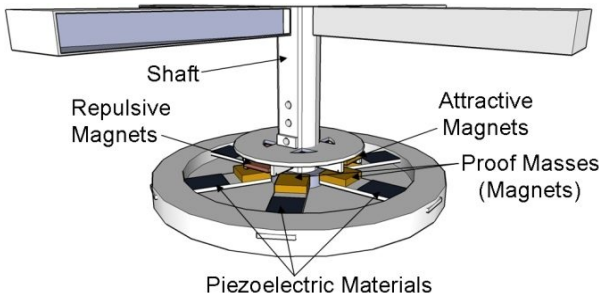

Figure 1. Concept of rotational Energy Harvesting System with piezoelectric and magnetic elements [3].

Tadesse et al. reports a multimodal energy harvesting device combining electromagnetic and piezoelectric energy harvesting[4]. His system consists of PZT bonded to a cantilever. The tip of the cantilever beam has an attached permanent magnet which, oscillates within a stationary coil fixed to the top of the package. Figure 2 shows the combined device of piezoelectric and electromagnetic transducers, in one device.

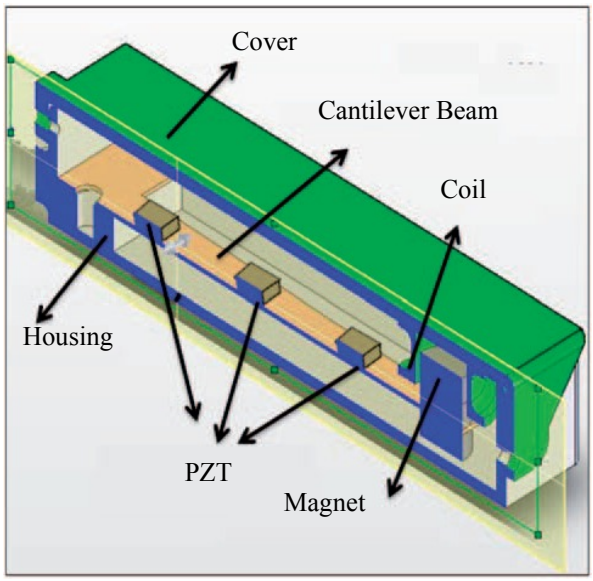

Figure 2. Sketch of a combined electromagnetic and piezoelectric energy harvester [3].

2. CONCEPT

The concept in this paper provides the combination of piezoelectric and electromagnetic power generation. The deflection of the piezoelectric bending element is excited by magnetic force. The magnetic field is additionally used by an inductive generator.
The concept should meet at least the following points:

- both transducers principles, and the electronics are integrated in a component
- suitable for mass production
- compact size
- designed for low frequencies
- large bandwidth (more than 20Hz)

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The basic idea was the concept of Lallert et. al. [3]. He used an inductive coil having a ferromagnetic core to expand instead of the permanent magnet on a beam end and at the other end to a power management integrated circuit. This system consists essentially of three components: the inductive unit, the piezoelectric bimorph in the center, and an electrical connection to the mounting, see Fig. 3. All components had to be matched, since they interact directly. The piezoelectric material and its dimensions determine the maximum permitted force at the tip. This force is a result of the area of the coil and the external magnetic field, which impacts on the induced voltage directly. However, one critical aspect is the energy harvesting electronic circuitry; its main requirement is an ultra low power consumption. Further, the entire harvesting unit has to be embedded in a suitable support, so that the individual components together are forming a unit. As base for the three components a rigid-flex circuit board material was chosen. This material is known from various technical applications, it is a combination of a conventional FR4 fiberglass circuit board material, and flexible polyamide, which are high-strength bonded under pressure. The rigid-flex boards are manufactured to customer demands in a sandwich design and provide considerable design freedom. In Fig. 3 can be seen, that the two rigid sections are at the ends and a flexible area is in the middle of rigid-flex board. The possibility of multilayer PCB parts allows the design of a compact integrated electric circuit. The contacts for the coil of the electromagnetic harvester can run directly along the neutral axis as interconnects in the polyimide. The coil itself is inserted into a hole in the left section and fixed there using adhesive.

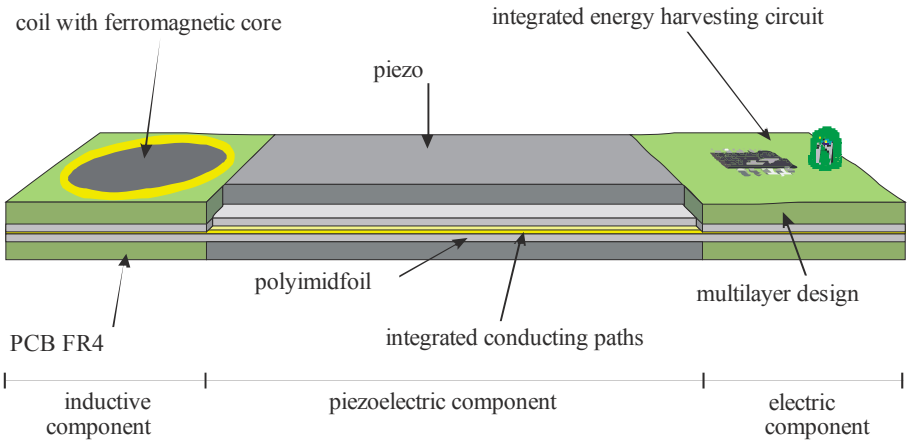

Figure 3. First concept of the Energy Harvesting System based on rigid-flex printed-circuit board

Based on these preliminary considerations the design of the energy harvester was more detailed. In Figure 4 the total concept of a test system is shown. Different to the later use, the harvesting unit and the permanent magnets are switched. The excitation of the deflection of the harvesting system will be caused by passing magnets, mounted on a rotating plate (Fig. 4 right). In each revolution of the plate the magnetic force causes an attracting excitation and so the PZT material is deformed.

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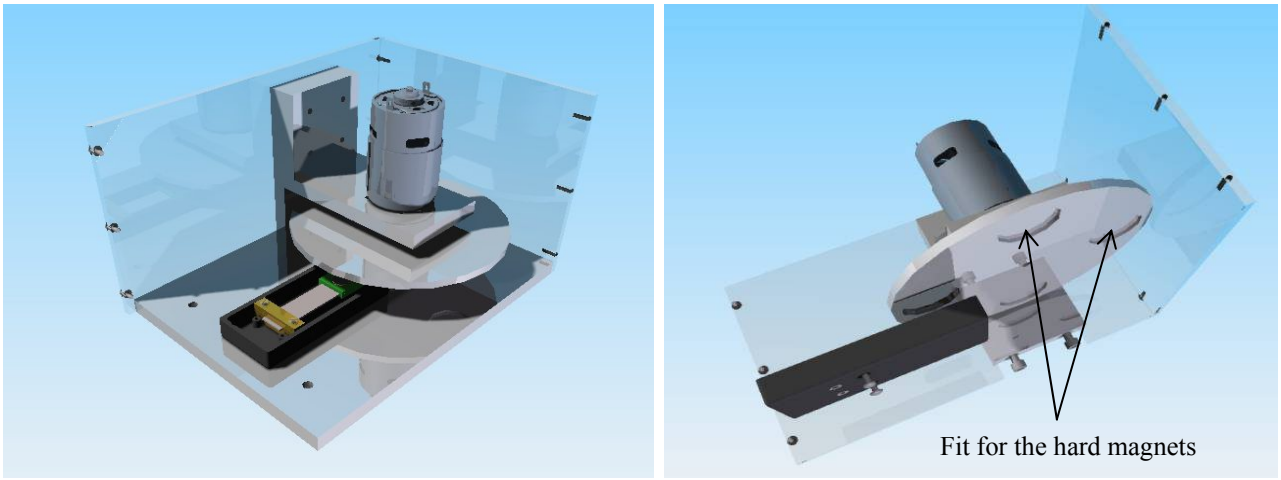

Figure 4. Concept of rotational Energy Harvesting System

Additional to the energy harvesting by PZT the changing of the magnetic field induces a voltage in the coil. So, both transforming systems harvest energy. A more detailed overview about the harvesting system is given in Figure 5.

Figure 5. Device consisting of a piezoelectric and electromagnetic part

For the design of the electronic component the, for energy harvesting specialized, chip LTC3588 from Linear Technology is used. The device offers full energy management, especially for low power sources. It acts as basis for the proposed integrated energy harvesting system. Using this pre-fabricated electronic makes it necessary to design both energy harvesters to match the requirements of the used electronic part. The LTC3588 has a bridge rectifier, a DC-DC converter, a hysteresis bases power management and a regulated MOSFET output stage. Only few external components are required to determine the parameters of the circuit, such as output voltage.
For the principal demonstrator a printed circuit board (PCB) milling machine has been used. Hence the miniaturization potential is limited in this step. However, for the design of the PCB only SMD components were used. For the characterization of each harvester type LEDs with two different colors (red and green) were implemented. A photograph of the electric circuit is given in Fig. 6.

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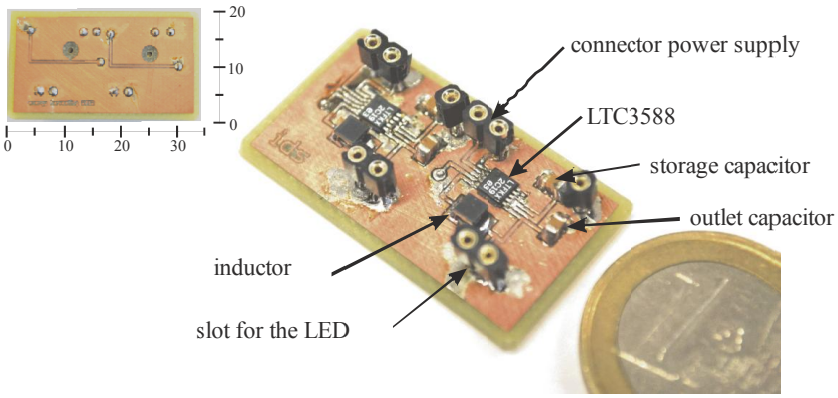

Figure 6. Layout of the electric circuit of the energy harvesting prototype; left: backside of the board

3. FABRICATION OF THE DEMONSTRATOR

After modeling the transducer, using equivalent circuit models, according to [5, 6, 7]. The major functional dimensions are fixed. The fabrication of each harvester type, piezoelectric and electromagnetic is described separately. At the end the implementation to a system will be explained.

For the piezoelectric harvester material from PI Ceramic was used. Kim has determined this material with the best features for energy harvesting devices [8]. The material PIC 255 shows the highest value of the piezoelectric constants (d g) which is proportional to its energy density. The dimension of the piezoelectric beam is 30 mm x 50 mm with a thickness of 500 µm. As support layer a copper laminated 200 µm polyimide foil was applied. There are two possible ways for the fabrication of the bimorph structure. On the one hand it is possible to connect in series to achieve double voltage and on the other hand a parallel connection. In the latter case the charge will be doubled and in this way the current. Here is assumed that the voltage generated by the two layers is equal because of the distance and symmetrical geometry to the neutral axis of the beam. Important for the connection is the polarization direction in which the piezos are applied. Unidirectional polarization is used for a series connection, if no or a conductive shim layer is inserted. The voltage in this sandwich-like structure can be received at a top and a bottom electrode. Depending on the polarization of the piezoelectric material we choose a parallel or serial circuit. Initial measurements with a parallel prototype have shown that the required voltage cannot be reached. The following Figure 7 shows the first prototype of the piezoelectric beam.

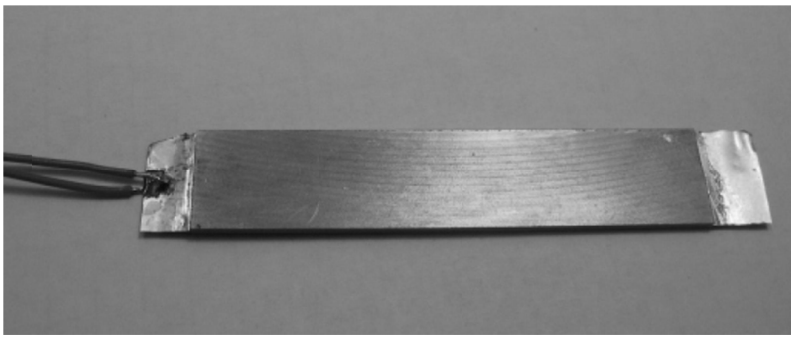

Figure 7: Photo of the first produced piezoelectric beam

For the maximization of the power output and of the inductive voltage it is necessary to put windings as much as possible in the system. In our case we design a hand-wounded coil with 1050 windings and a soft magnetic core consisting of CoFe as a material with a high magnetic permeability. After all the parts, piezoelectric and electromagnetic are combined with the electronic. Figure 8 and 9 show the first prototype of the implemented system.

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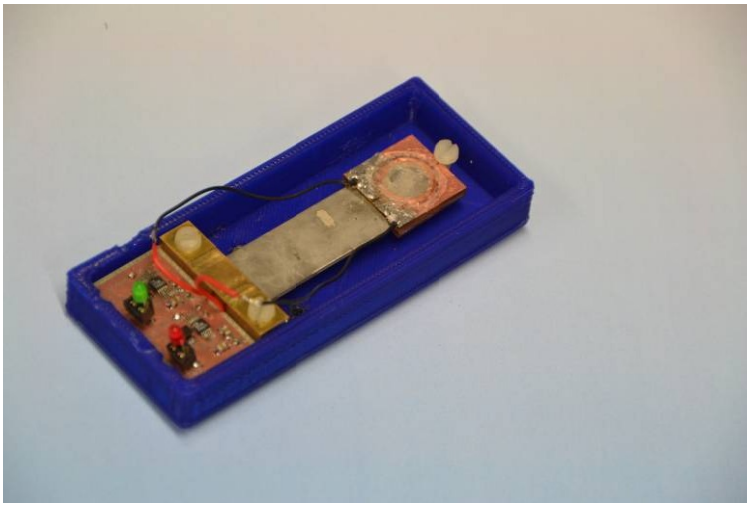

Figure 8. Demonstrator of the Energy Harvesting System with piezoelectric and electromagnetic part

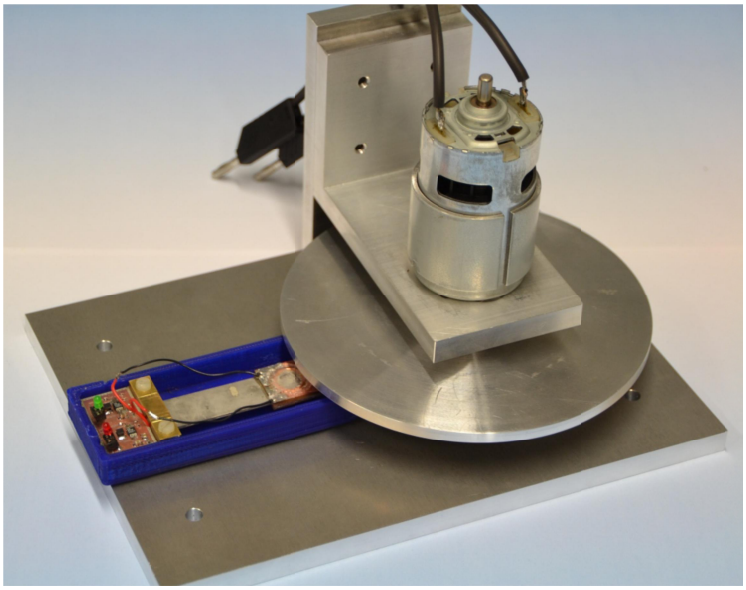

Figure 9. Photograph of the realized demonstrator of the Energy Harvesting System with piezoelectric and electromagnetic part

4. EVALUATION

Both energy harvesting concepts were evaluated separately. For a better comparability the results were shown together in one diagram. In the following Fig. 10 the voltage depending over the motor revolution is described. Each harvester was evaluated by different gaps between the soft-magnetic core and the hard magnets placed in the rotating disk. The gap varies between 3.5 and 5.8 mm.

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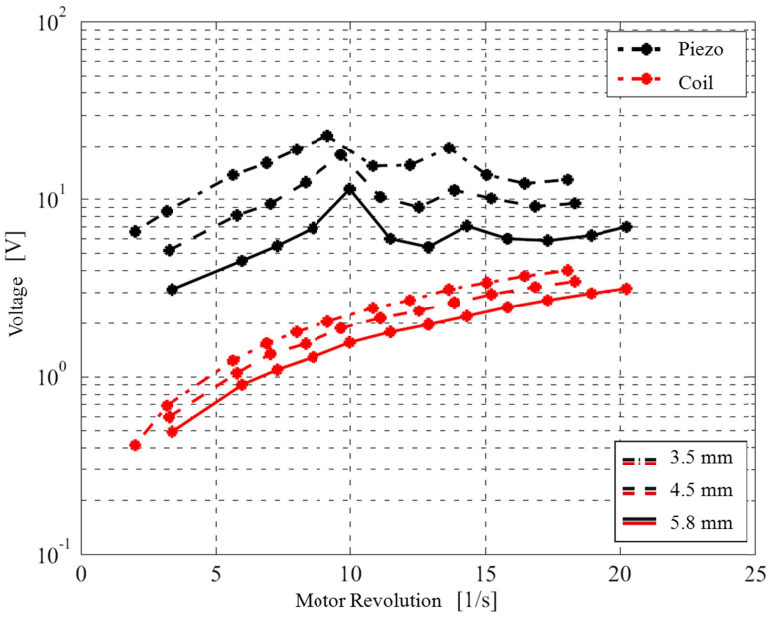

Figure 10. Gradient of the voltage of both energy harvesters depending on the motor revolution

The gradients of the voltage show a clear resonance. Thereby the resonance is at lower frequency with small gap. The induced voltage arises linear with an increase of the motor resolution. At low frequencies the generated voltage by the piezoelectric harvester is ten times higher than of the voltage induced by the coils. With the increasing motor revolution this difference is smaller. At higher motor revolutions, the induced voltage of the coil rises above the voltage of piezo. From this point of view a broadband frequency spectrum can be used as excitation for such a kind of energy harvesting system. The following Figure 11 shows a similar behavior as shown before for the generated power of the energy harvesting device.

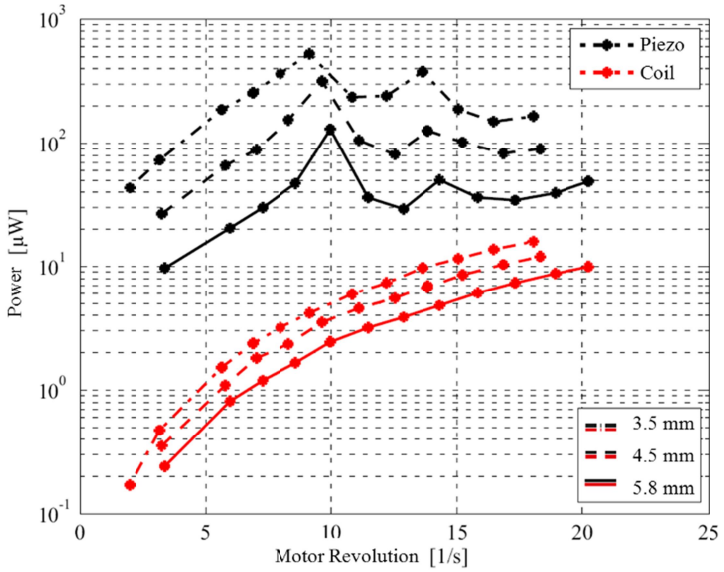

Figure 11: Gradient of the power of both energy harvesters depending on the motor revolution

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Figure 12 shows the first three Fourier coefficients of the excitation force time behavior. The horizontal lines mark the 3 dB range around the resonance frequency. The grey layered area marks the motor revolution range where from the theoretical point of view the piezo will be excited in resonance.

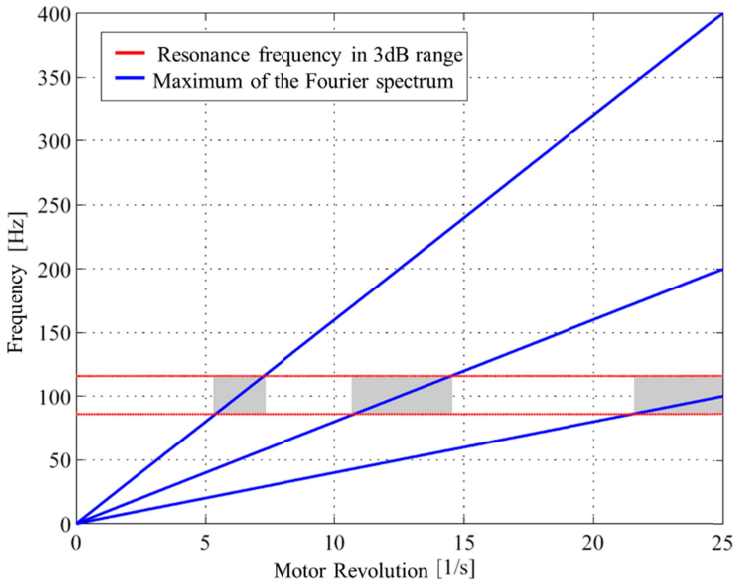

Figure 12: Position of the three highest peaks in the frequency spectrum at different motor revolutions

5. CONCLUSION

The combination of two vibration energy harvesting principles, piezoelectric and electro-magnetic, shows a well possibility to fabricate a broadband energy harvesting system. The evaluation shows that the described combination of the two harvesting principles above makes it possible to fabricate a broadband demonstrator.

REFERENCES

[1] Dembowski: Energy Harvesting for the Microelectronic. VDE-Verlag, 2011

[2] Twiefel, J. and Westermann, H., "Survey on broadband techniques for vibration energy harvesting," Journal of Intelligent Material Systems and Structures (2013). doi:10.1177/1045389X13476149.

[3] Lallart et al.: Small-scale Piezoelectric Energy Harvesting Devices using Low-energy-density Sources. Journal of the Korean Physical Society, Vol. 57, No. 4, 2011

[4] Tadesse, Y.; Zhang, S.; Priya, S.: Multimodal Energy Harvesting System: Piezoelectric and Electromagnetic, Journal of Intelligent Material Systems and Structures, 2009

[5] Twiefel, Jens, et al. "Model-based design of piezoelectric energy harvesting systems." Proc. SPIE. Vol. 6169. 2006.

[6] Richter, Björn, and Jens Twiefel. "Parameter identification of piezoelectric bimorphs for dynamic applications considering strain and velocity dependent effects." Proc. SPIE. Vol. 7288. 2009.

[7] Marin, Anthony, et al. "Improved pen harvester for powering a pulse rate sensor." Proc. of SPIE Vol. Vol. 8341. 2012.

[8] KIM, Hyeoungwoo: IMPEDANCE ADAPTATION METHODS OF THE PIEZOELECTRIC ENERGY HARVESTING, The Pennsylvania State University, Diss., 2006

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